THE OPTICAL CONSTANTS OF CRYSTALS OF SELENIUM AND TELLURIUM FOR WAVE LENGTHS FROM 3000 TO 5000 ANGSTROMS

BY

RAYMOND FOSTER MILLER

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF THE GRADUATE COLLEGE OF THE STATE UNIVERSITY OF IOWA

1923

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By R. F. Miller

ABSTRACT

The measurements were made by a photographic method, for two positions of the crystal, (1) with the optic axis parallel, and (2) with the axis perpendicular to the plane of incidence. Two sets of optical constants were found for each substance. For selenium, in the parallel position the index of refraction was found to vary from 3.4 to 4.4, and the reflecting power from 0.38 to 0.46; in the perpendicular position the index varies from 2.3 to 3.1, and the reflecting power from 0.41 to 0.34. For tellurium, in the parallel position the index varies from 1.9 to 2.9, and the reflecting power from 0.10 to 0.27; in the perpendicular position the index varies from 1.7 to 2.7, the reflecting power from 0.09 to 0.23. The average error is estimated to be about 5 per cent. The accuracy is greatest for the middle range of wave-lengths, 3500-4000 A.

I. INTRODUCTION

When plane-polarized light is reflected from the polished surface of an absorbing medium it becomes in general elliptically polarized. The shape of the vibration ellipse formed by reflection depends upon the angle of incidence and upon the optical constants (coefficient of absorption and index of refraction) of the reflecting material. Equations have been developed by Drude[1] which connect the optical constants and angle of incidence with the phase angle and azimuth of the ellipse. Thus if the form of the elliptical vibration can be found for some known angle of incidence, the optical constants may be calculated.

There are two general methods of determining the vibration form of reflected light. The first is the polarimetric method, in which the constants of the ellipse are found visually with the aid of a Babinet compensator and analyzing Nicol. The second is an indirect photo-

[1] P. Drude: Ann. der Phys. *34*, p. 528; 1888.

graphic method, first suggested by Voigt.[2] This latter plan was followed in the present investigation.

It has been found experimentally by Tate[3] that the optical constants obtained by reflection vary considerably with the degree of polish of the metallic surface and the character of the polishing process. This difficulty may be avoided in case of certain substances by using the faces of crystals. There is another and more important advantage in the use of crystals. If the substance should be doubly refracting, it may be possible to determine two sets of optical constants by taking measurements with the axis of the crystal first in one direction and then in another direction at right angles to the first.

Selenium and tellurium are well adapted to use in this way, as they crystallize in slender hexagonal needles with faces which are often nearly perfect. Selenium has been investigated by Skinner[4] and Weld[5] for the visible spectrum, and found to be doubly refracting. Van Dyke[6] found the same to be true of tellurium.

The object of the present research was to find the optical constants of these two substances for the ultra violet region of the spectrum, and to check the work of Weld and Van Dyke for a part of the visible spectrum.

II. APPARATUS

The apparatus used was the Crystelliptometer described by Weld (loc. cit.[5]). The Hilger constant deviation monochromator used by Weld was replaced by one built according to plans given by Pfund,[7] and an iron arc of the Pfund[8] type was used as a source of light. The monochromator was not calibrated, but the wave-lengths were determined by identifying lines in the iron spectrum. In the ultra violet this was done by means of the fluorescence produced upon a thin plate of uranium glass.

The Crystelliptometer was accurately aligned with the beam of light from the polarizer by utilizing the telescope of the spectrometer upon which the crystal was mounted. A narrow beam, after passing through the telescope was observed through the camera tube of the Crystelliptometer, and the latter adjusted so that the beam was

[2] Voigt: Physik. Zeitschr. *2*, 203, 1901.
[3] J. T. Tate: Phys. Rev. *34*, p. 321; 1912.
[4] C. H. Skinner: Phys. Rev. N.S. *9*, p. 148; 1917.
[5] L. D. Weld: J. O. S. A. & R. S. I. *6*, p. 67; 1922.
[6] G. D. Van Dyke: J. O. S. A. & R. S. I. *6*, p. 919; 1922.
[7] A. Pfund: Phys. Rev. *7*, p. 291; 1916.
[8] A. Pfund: Astrophysical Jour. *27*, p. 296; 1908.

centered. The accurate alignment secured by this means prevented any shift of the spot-pattern with changes of focus and wave-length. When a photograph was desired with ultra violet light, all adjustments of the apparatus were made by aid of visible light, and then the wave-length was changed. A new crystal-mounting was constructed, which permitted adjustments about three mutually perpendicular axes. Two positions of the crystal were used: (1) axis horizontal (parallel to the plane of incidence); (2) axis vertical (perpendicular to the plane of incidence). The crystal could be turned from one of these positions to the other in its own plane, so that a photograph of the reflected beam could be secured with the crystal in each position successively with only one setting of the Crystelliptometer.

III. THEORY AND CALCULATIONS

Voigt (loc. cit.[2]) and Minor[9] give the following equations for the coordinates of any dark spot on a spot-pattern produced by a double wedge-system such as was used in this investigation: (see Figs. 1 and 2.)

$$\delta_1 = \delta' + \Delta = 2\pi n, \text{ or } \delta' = 2\pi n - \Delta \quad (1)$$

$$\theta_1 = -\psi + \beta \pm \tfrac{1}{2}(2n+1)\pi \quad (2)$$

$$\delta_2 = \delta'' + \Delta = (2n+1)\pi, \text{ or } \delta'' = (2n+1)\pi - \Delta \quad (3)$$

$$\theta_2 = +\psi + \beta \pm \tfrac{1}{2}(2n+1)\pi \quad (4)$$

In these equations Δ = difference of phase of the two components of the incident vibration, δ' and δ'' are the relative retardations introduced by the Babinet compensator, δ is the total phase difference, θ = angle of rotation in the second wedge-system (rotator) at the point of passage, β = angle between the x-axis and the plane of transmission of the analyzer, and ψ = azimuth of the plane-polarized light into which the elliptical vibration is changed by the wedge-system. n is any one of the sequence of numbers 0, 1, 2, 3, 4 . . . . . δ and θ may be used as the coordinates of a system of lines, with the δ-axis horizontal, and the θ-axis vertical. Equation (1) gives a system of lines parallel to the θ-axis, which are the loci of points where the light is plane-polarized. Equation (2) gives a set of lines parallel to the δ-axis, which are the loci of points where the aximuth of the plane-polarized vibration is perpendicular to the transmission-axis of the analyzer. The intersections of the lines (δ_1, θ_1) give points of zero intensity or dark spots. A second system of lines is given by equations (3) and (4), whose intersections (δ_2, θ_2) give points of zero intensity. These equations show

[9] Minor. Ann. der Phys. *10*, p. 581; 1903.

how the two systems of spots shift as changes are made in the phase angle Δ or the azimuth ψ of the incident light. If the relative phase Δ is changed by an amount Δ_1 then from equations (1) and (3),

$$\delta' = -\Delta + 2n\pi - \Delta_1, \text{ and } \delta'' = -\Delta + (2n+1)\pi - \Delta_1.$$

This shows that the δ-coordinate of each spot is changed by the same amount, so that the entire spot-pattern is shifted horizontally. The situation is quite different when ψ is changed. Let the amount of the change be ϵ. Then from equations (2) and (4),

$$\theta_1 = -(\psi+\epsilon)+\beta \pm \tfrac{1}{2}(2n+1)\pi = -\psi+\beta \pm \tfrac{1}{2}(2n+1)\pi - \epsilon.$$

$$\theta_2 = +(\psi+\epsilon)+\beta \pm \tfrac{1}{2}(2n+1)\pi = +\psi+\beta \pm \tfrac{1}{2}(2n+1)\pi + \epsilon.$$

This shows that the spots of the two systems are shifted vertically by the same amount but in opposite directions.

Application of the Equations to Data from Plate Measurements. Take as coordinate axes the lines where $\delta' = 0$, and $\theta = 0$. From eq. (1), when $n = 0$, $\delta_1 = 0$ and $\delta' = -\Delta$. Then if $\delta' = 0$, (along the y-axis) $\Delta = 0$. This means that the column of spots for which $\Delta = 0$ lies upon the y-axis.

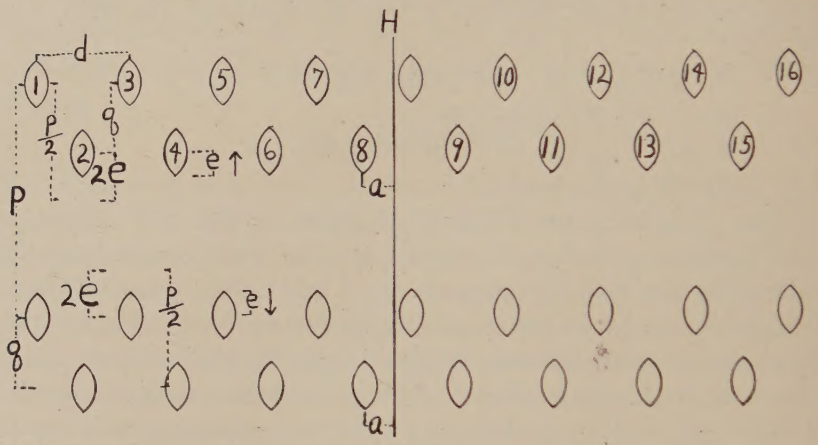

FIG. 1. *Sketch of a typical spot-pattern.*

This is the case for the comparison spot-pattern, photographed when a plane-polarized beam is admitted into the Crystelliptometer without reflection. But when the incident plane-polarized beam is reflected from a polished surface, (assuming no elliptical polarization) the plane of vibration, as seen by the observer, is rotated through 90 degrees. This is equivalent to a phase change $\Delta = \pi$ between the components of the original vibration. Then from eq. (1) $\delta' = -\pi$, which means that there has been a sidewise shift of the entire spot-pattern through a distance $d/2$, if d is defined as the distance between adjacent columns belonging to the same system. As may be seen from eq. (1), d corre-

sponds to a phase change of 2π. From eq. (3), when $n=0$ and $\Delta=\pi$, $\delta_2=0$. Thus we see that a column of spots belonging to the second system lies along the y-axis. For convenience in measurement this latter column was chosen as the "zero column," and all shifts referred to its position when $\Delta=\pi$. If the reflected beam is elliptically polarized, the relative phase difference between the components of the incident beam is Δ, and the change of phase compared to a plane-polarized reflected beam is $\pi-\Delta$. This change of phase results in a shift of the spot-pattern through a distance a. (See Fig. 1).

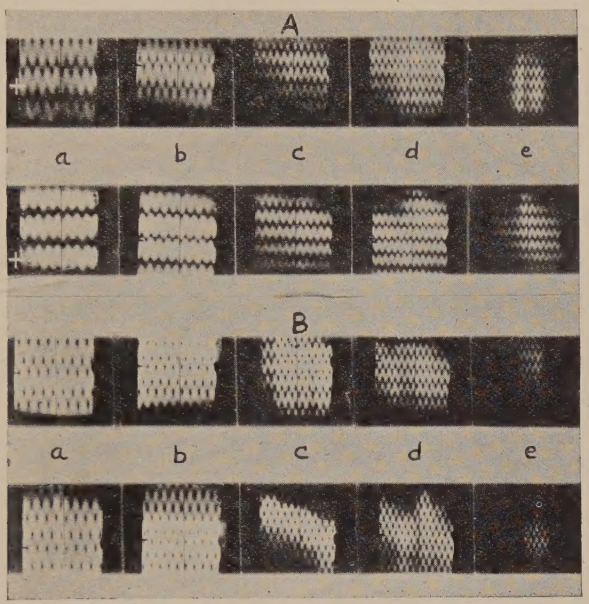

FIG. 2. *Photographs of spot-patterns of selenium (A), and tellurium (B).*
Upper row in each case, crystal axis parallel to the plane of incidence.
Lower row, crystal axis perpendicular to the plane of incidence. Wave-lengths in Angstroms: (a) 4529; (b) 4068; (c) 3440; (d) 3200; (e) 3008. Angle of incidence 70 degrees.

The phase-change may also be represented by the expression: $2\pi a/d$, since a shift d represents a change of phase of 2π. Thus $\pi-\Delta=a/d \times 360°$. As an example, plate 42H ($\lambda=3750$, $\phi=65°$), gives $a=0.196$; $d=1.624$ mm. Then $\pi-\Delta=\dfrac{0.196}{1.624}\times 360°=43.5°$, and $\Delta=136.5°$.

In eq. (2) let $\beta=0$, (transmission axis of the analyzer horizontal) and $\psi=\psi_0-\psi_1$. Then $\theta_1=-(\psi_0-\psi_1)\pm\frac{1}{2}(2n+1)\pi$. Here ψ_0 is the azimuth of the plane-polarized light incident upon a surface, and ψ_1

is the change in aximuth produced by the quartz wedges of the Crystelliptometer. In practice ψ_0 was taken equal to 45°, so that $\theta_1=\psi_1-45°\pm\frac{1}{2}(2n+1)\pi$. Similarly from eq. (4), $\theta_2=\psi_1+45°\pm\frac{1}{2}(2n+1)\pi$. Thus the change in aximuth ψ_1 is proportional to the change in the y-coordinate θ. Represent this shift by e. Then a shift e means an azimuth change of $e/p\times180°$, since one vertical spot-interval p involves a change of 180° or π (see eq. 2). Thus $\psi_1=e/p\times180°$. Now

$$\psi=\psi_0-\psi_1=45°-\left(\frac{e}{p}\times180°\right) \tag{5}$$

It is very convenient to measure the distance q between adjacent rows rather than the y-coordinate of any spot. As shown in fig. 1, $q=p/2-2e$, or $e=(p-2q)$. Substituting in equation (5).

$$\psi=45°-\frac{p-2q}{4p}\times180°=\frac{q}{p}\times90°\,. \tag{6}$$

This is the relation used for calculating ψ. For example, plate 42H gives $q=1.08$; $p=4.32$ mm. Then $\psi=\dfrac{1.08}{4.32}\times90°=22.5°$.

Equations of the Optical Constants. Drude (loc. cit.[1]) has derived equations for the optical constants of doubly refracting crystalline substances, and their applicability in this connection has been discussed by Sieg.[10]

$$\frac{\cos 2\psi_1+i\sin 2\psi_1\sin\Delta_1}{1-\sin 2\psi_1\cos\Delta_1}=\frac{\sqrt{\alpha}}{\cos\phi}-\sqrt{\gamma}\cos\phi \tag{7}$$

$$\frac{\cos 2\psi_2+i\sin 2\psi_2\sin\Delta_2}{1-\sin 2\psi_2\cos\Delta_2}=\frac{\sqrt{\gamma}}{\cos\phi}-\sqrt{\alpha}\cos\phi \tag{8}$$

In these equations ϕ is the angle of incidence, ψ is the azimuth angle, Δ is the relative phase of the x and y components of the elliptical vibration, and α and γ are complex constants. The subscripts (1) and (2) refer to the two positions of the crystal, with axis respectively horizontal (parallel to the plane of incidence) and vertical (perpendicular to the plane of incidence).

Let

$$\alpha=A_{11}+iA_{12}\,;\quad\gamma=A_{31}+iA_{32}$$

[10] L. P. Sieg. J. O. S. A. & R. S. I. *6*, p. 448; 1922.

Then if χ is such an angle that $\tan \chi = \frac{A_{12}}{A_{11}}$, and if $\tan \Sigma = \frac{A_{32}}{A_{31}}$, then

$$K_1 = \tan \frac{\chi}{2}, \text{ and } K_2 = \tan \frac{\Sigma}{2} \tag{9}$$

Here K_1 and K_2 are the absorption coefficients.

$$N_1^2 = \frac{2 \sin \frac{\chi}{2} \cos^3 \frac{\chi}{2}}{A_{12}}; \quad N_2^2 = \frac{2 \sin \frac{\Sigma}{2} \cos^3 \frac{\Sigma}{2}}{A_{32}} \tag{10}$$

N_1 and N_2 are the indices of refraction.

$$R_1 = \frac{N_1^2(1+K_1^2)+1-2N_1}{N_1^2(1+K_1^2)+1+2N_1}; \quad R_2 = \frac{N_2^2(1+K_2^2)+1-2N_2}{N_2^2(1+K_2^2)+1+2N_2} \tag{11}$$

R_1 and R_2 are the coefficients of reflection, or reflecting powers.

A Sample Calculation of the Optical Constants. Assume the following data, obtained from plates 77H and 77V, by the method previously described: (The crystal was selenium). $\phi = 75°$; $\Delta_1 = 106.7°$; $\psi_1 = 14.8°$; $\cos 2\psi_1 = 0.8695$; $\sin 2\psi_1 = 0.494$; $\cos \Delta_1 = -0.2874$; $\sin \Delta_1 = 0.958$; $\Delta_2 = 69°$; $\psi_2 = 13.8°$; $\cos 2\psi_2 = 0.8862$; $\sin 2\psi_2 = 0.4633$; $\cos \Delta_2 = 0.3584$; $\sin \Delta_2 = 0.9336$; $\cos \phi = 0.2588$. Substituting in eqs. (7) and (8),

$$\frac{0.8695 + i\,0.494 \times 0.958}{1-(0.494 \times -0,2874)} = \frac{\sqrt{\alpha}}{0.2588} - 0.2588\sqrt{\gamma}$$

$$\frac{0.8862 + i\,0.4633 \times 0.9336}{1-(0.4633 \times 0.3584)} = \frac{\sqrt{\gamma}}{0.2588} - 0.2588\sqrt{\alpha}$$

From which $\alpha = 0.0225 + i\,0.0342$, and $\gamma = 0.062 + i\,0.0806$. Substituting values of A_{11}, A_{12}, A_{31}, A_{32}, in eq. (9), $K_1 = 0.539$, and $K_2 = 0.495$. From eq. (10),

$$N_1^2 = \frac{2 \times 0.475 \times 0.682}{0.0342} = 18.9; \quad N_1 = 4.35.$$

$$N_2^2 = \frac{2 \times 0.443 \times 0.72}{0.0806} = 7.9; \quad N_2 = 2.81.$$

Substituting values of N and K in eq. (11),

$$R_1 = \frac{(18.9 \times 1.29)+1-8.7}{(18.9 \times 1.29)+1+8.7} = 0.49; \quad R_2 = \frac{(7.9 \times 1.245)+1-5.6}{(7.9 \times 1.245)+1+5.6} = 0.32$$

Sample Data from Plate Measurements

Plate No. 42V, $\lambda = 3750$ A, $\phi = 65°$. (See FIG. 1).

x-coordinates of dark spots.				$x-x_0$ (−)	$x-x_0$ (+)	y-coordinates of rows.	
Hair	23.51		mm	mm	mm	mm	q
1	17.21	9	24.50	6.30	0.99	24.77	
2	18.04	10	25.25	5.47	1.74	23.72	1.05
3	18.79	11	26.10	4.71	2.59	20.53	
4	19.63	12	26.92	3.88	3.41	19.43	1.10
5	20.48	13	27.75	3.03	4.24		1.08 Av.
6	21.29	14	28.51	2.22	5.00		
7	22.04	15	29.35	1.47	5.84		
8	22.84	16	30.18	0.67	6.67	$d = 1.624$, from comparison plate.	
				27.75	30.48		
					−27.75	$p = 4.32$, from comparison plate.	
					sum 2.73		

$a' = 2.73/16 = 0.17$ $\quad \pi - \Delta_2 = a/d \times 360° = 43.5°$ $\quad \Delta_2 = 136.5°$

c $\quad 0.026$

a $\quad 0.196$ $\quad \psi_2 = q/p \times 90° = 22.5°$

Explanation: a' is the sidewise shift, and is the algebraic sum of the x-coordinates divided by the number of spots measured. c is a correction which must be applied because the central column of spots may not lie exactly on the hair-line when $\phi = 0$. c is found in the same way as a', except that the plate is taken in the comparison position, i.e. the beam of plane-polarized light enters the Crystelliptometer directly without reflection. d and p are the average spot-intervals in the horizontal and vertical directions respectively. They may be obtained either from the data given above or from the comparison plate.

IV. TABLES OF OPTICAL CONSTANTS

TABLE 1. *Optical Constants of Selenium (averages). λ is the wave-length in Angstroms, K is the absorption coefficient, N is the index of refraction and R is the reflecting power. The subscripts (1) and (2) refer to the parallel and the perpendicular position respectively.*

λ	K_1	K_2	N_1	N_2	R_1	R_2
3008	0.47	0.93	3.4	2.3	0.38	0.41
3200	0.60	0.89	3.4	2.3	0.44	0.38
3440	0.80	0.79	3.6	2.6	0.51	0.36
3750	0.61	0.68	3.8	2.9	0.52	0.38
4068	0.86	0.46	3.6	3.3	0.54	0.36
4529	0.51	0.41	4.4	3.1	0.46	0.34
4958	0.60	0.57	3.4	3.4	0.42	0.26

Each value given in the tables is the average of four separate determinations, each made for a different angle of incidence, ranging from 55° to 80°. Two plates are required for each angle of incidence, and

one or two additional plates are taken in the comparison position. Thus each determination of the optical constants involved the exposure and measurement of nine or ten photographic plates. Each column of

TABLE 2. *Optical Constants of Tellurium (averages). Symbols have the same meaning as in Table I.*

λ	K_1	K_2	N_1	N_2	R_1	R_2
3008	0.09	0.30	1.9	1.66	0.10	0.09
3200	0.14	0.32	2.1	1.6	0.14	0.12
3440	0.13	0.35	2.4	1.9	0.18	0.15
3750	0.17	0.35	2.5	2.0	0.21	0.16
4068	0.21	0.37	2.8	2.4	0.24	0.22
4529	0.26	0.42	3.1	2.8	0.30	0.29
4900	0.24	0.34	2.9	2.7	0.27	0.23

spots was measured at least three times, and each row (y-coordinates) five times. The values of the coordinates given in the sample data are averages.

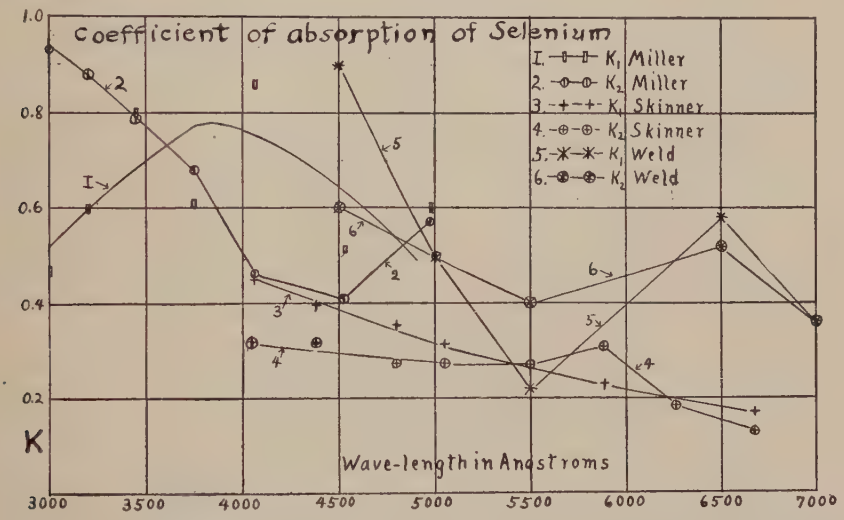

FIG. 3. *Coefficients of absorption of selenium, as found by three investigators. The subscripts (1) and (2) refer to the parallel and the perpendicular position of the crystal respectively.*

V. DISCUSSION OF ERRORS

The chief errors involved are (1) imperfect adjustment of the apparatus, and (2) errors of judgment in estimating the positions of the centers of the dark spots when measuring their coordinates with the comparator microscope. Errors of the latter kind may be estimated by noting the deviation from the average. The quantities d and p

can be measured more accurately than a or q, and usually their values obtained from several plates at the same wave-length agree to one part in 150 or 200. q is hard to measure because the spots are elongated and sometimes triangular, so that the centers are hard to locate. a is a small quantity, often only one tenth of a millimeter, and rarely over half a millimeter. Its value increases with the angle of incidence, but does not become large enough for accurate measurement until the angle of incidence reaches 65° or 70°. An estimate of the per cent error in measuring a and q gives six for the former, and three for the latter. Since the values of Δ and ψ are proportional to a and q respectively, they will be in error by these same percentages. The formulae

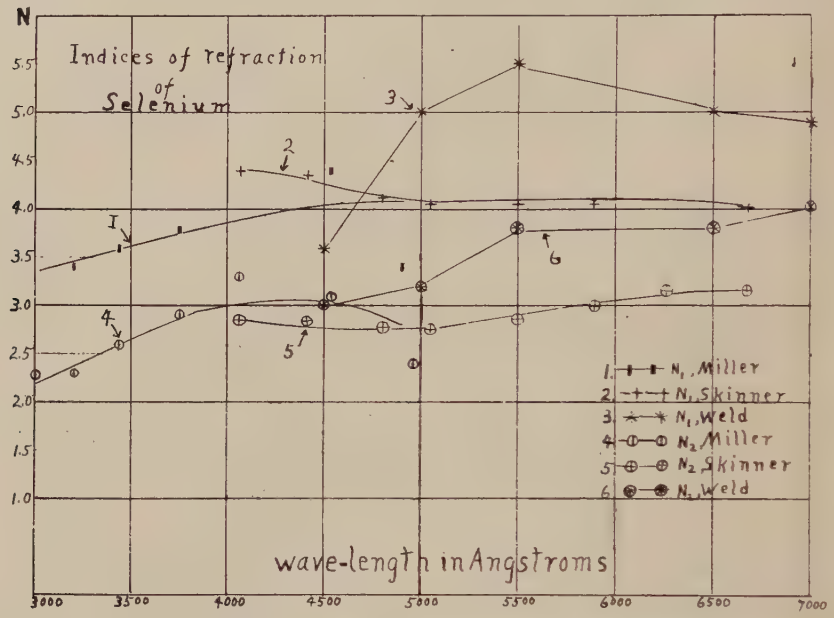

FIG. 4. *Indices of refraction of selenium. Subscripts have the same meaning as in fig. 3.*

for the optical constants are so complicated that it is difficult to discover what effect errors in the values of Δ and ψ have upon them. The result of a number of test calculations shows that a change of 3° in Δ results in a change of 0.15 in N, and 0.1 in K. A change of 1° in ψ makes a change of approximately 0.1 in N, and 0.1 in K. The corresponding values of R are only slightly affected—about 0.01. We may conclude that a single determination of the optical constants may be in error to the following extent: index of refraction 0.25; absorption coefficient 0.2; reflecting power 0.02. The instrumental errors are not

counted in this estimate, as it is not possible to determine the amount. Since the variations among successive determinations of the optical constants are usually not greater than the values given above, it is believed that the errors due to imperfect adjustments of the apparatus are for the most part quite small. The accuracy is greater in the ultra violet region than for the visible region. The maximum accuracy should be attained at about $\lambda = 3750$ Angstroms for the apparatus used, because of the clear sharp spots, and fair values of a and q. By replacing the quartz wedges used by others of proper design, the apparatus could be used satisfactorily throughout the visible spectrum.

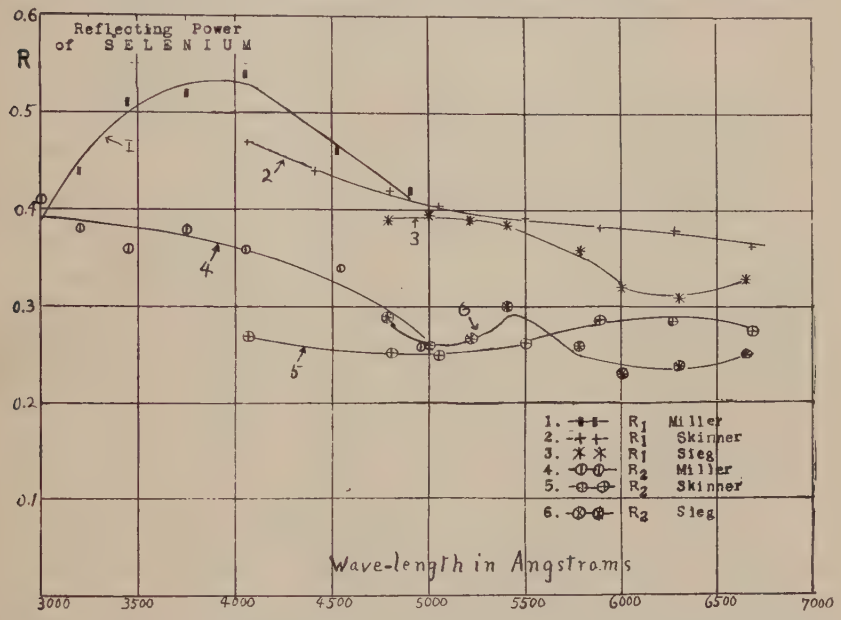

FIG. 5. *Reflecting powers of selenium. The subscripts have the same meaning as in fig 4.*

It is believed that the values of the indices of refraction and reflecting powers of both substances, and the coefficients of absorption of tellurium are correct within 5 per cent on an average. The constants for tellurium are more reliable than those for selenium, due to increased skill in handling the apparatus. The values of the coefficients of absorption of selenium show large variations and may be in error by ten to twenty per cent.

VI. COMPARISON WITH THE WORK OF OTHERS

A comparison of the values obtained by the writer and by several other investigators leads to the following conclusions: (See Figs. 3-8).

Skinner's (loc. cit.[4]) results are the most consistent and probably the most accurate yet obtained for a single crystal of selenium. W. Meier's[11] results are in good agreement with Skinner's values for the vertical position. Meier used the same method as the one here presented,

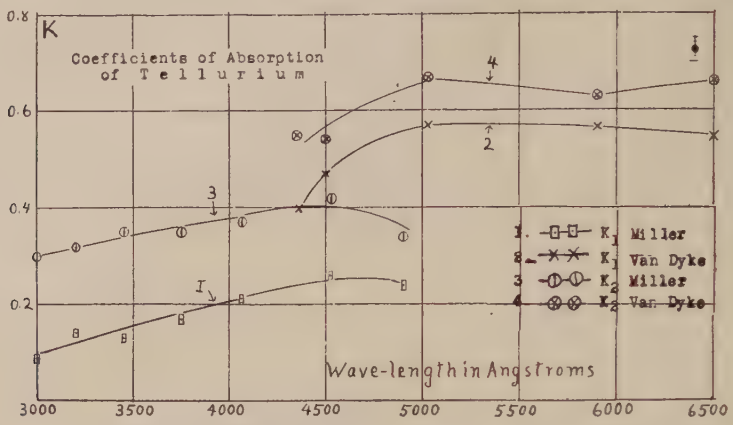

FIG. 6. *Coefficients of absorption of tellurium, as found by two investigators. The subscripts (1) and (2) refer to the parallel and the perpendicular position of the crystal respectively.*

but the selenium used was a cast plate. As pointed out by Sieg (loc. cit.[10], p. 460) the crystals in this case are likely to stand end on at the surface, so that the optical constants obtained should be nearer to the

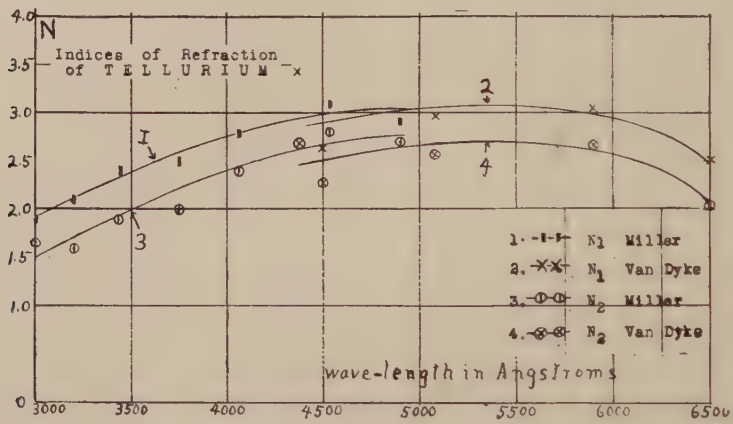

FIG. 7. *Indices of refraction of tellurium. Subscripts have the same meaning as in fig. 6.*

values for the vertical position (axis perpendicular to the plane of incidence) of the crystal. Hulburt's[12] and Sieg's (loc. cit.[10] p. 459)

[11] W. Meier: Ann. der Phys. *31*, p. 1017; 1910.
[12] Hulburt: Astrophys. Jour. *42*, p. 222, 1915.

results on reflecting power agree well with those of Meier within the range measured, and this fact lends additional support to the validity of Skinner's work. Weld's measurements (calculated by Sieg, loc. cit.[10] p. 456) are doubtful, as only one angle of incidence was used (60)°, and at this angle the shift a is too small to be measured with accuracy, especially when the spots are large. My values of the optical constants are in fair agreement with those of Skinner, Meier, Sieg and Hulburt, wherever the determinations overlap. In case of tellurium my values agree fairly well with those of Van Dyke (loc. cit.[6] p. 917) and Sieg,[13] and the consistency of the various measurements is better than for selenium.

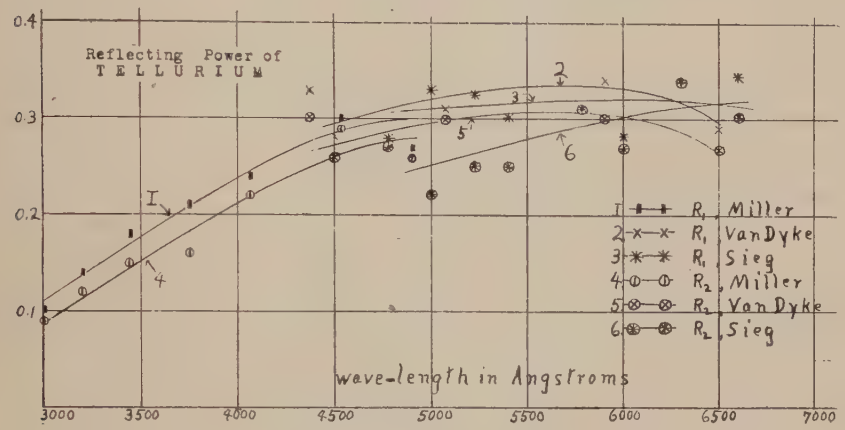

FIG. 8. *Reflecting powers of tellurium.*

VII. CONCLUSIONS

1. The optical constants of isolated crystals of selenium and tellurium have been obtained for wave-lengths from 3000 to 4300 Angstroms for the first time.

2. The region of maximum accuracy for the particular apparatus used is from 3500 to 4000 Angstroms.

3. Both selenium and tellurium have two sets of optical constants. The index of refraction and reflecting power for each substance are greater for the parallel than for the perpendicular position. The reverse is true of the coefficient of absorption of tellurium. The coefficients of absorption of selenium show wide variations for different parts of the spectrum, but average about the same for the two positions of the crystal.

[13] Sieg: J.O.S.A. & R.S.I., 7, p. 147; 1923.

4. There is fair agreement between the values obtained in the visible spectrum with those of other investigators.

5. The extension of the measurements farther into the ultra violet was prevented by absorption of light in the optical apparatus, and by low reflecting power of the crystals for short waves.

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